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Comparative analysis of the transversities and the longitudinally polarized distribution functions of the nucleon

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Abstract

A first empirical extraction of the transversity distributions for the u - and d -quarks has been done by Anselmino *et al.* based on the combined global analysis of the measured azimuthal asymmetries in semi-inclusive deep inelastic scatterings and those in $e^+e^- \rightarrow h_1h_2X$ processes. Although with large uncertainties, the determined transversity distributions already appear to reveal a remarkable qualitative difference with the corresponding longitudinally polarized distributions. We point out that this difference contains very important information on internal spin structure of the nucleon.

As a member of three independent twist-2 parton distribution functions, the transversity distributions, usually denoted as $\Delta_T q(x)$, or $h_1^q(x)$, or $\delta q(x)$, are believed to contain valuable information for our deeper understanding of internal spin structure of the nucleon [1],[2]. Unfortunately, because of their chiral-odd nature, we cannot access them directly through the standard inclusive deep-inelastic scatterings. They can be accessed only through physical processes which accompany quark helicity flips. At present, the cleanest way is believed to measure the transverse spin asymmetry A_{TT} in Drell-Yan processes in $p\bar{p}$ collisions at high energies [3]-[6]. Another promising (and also practical) way is to measure the so-called transverse single-spin asymmetries in the semi-inclusive deep inelastic scatterings [7]. A main drawback here as compared with the Drell-Yan measurement is our limited knowledge on the spin-dependent fragmentation mechanism implemented by the so-called Collins function [8]. What gave a drastic breakthrough toward the success of this strategy is the recent independent measurement

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of the Collins function in unpolarized $e^+e^- \rightarrow h_1 h_1 X$ processes by the Belle Collaboration at KEK [9]. Armed with this new information, Anselmino *et al.* carried out a combined global analysis [10] of the azimuthal asymmetries in semi-inclusive deep inelastic scatterings measured by the HERMES [11] and COMPASS Collaborations [12], and those in $e^+e^- \rightarrow h_1 h_2 X$ processes by the Belle Collaboration [9]. Although with large uncertainties, this enables them to determine the transversity distributions and the Collins functions of the u - and d -quarks, simultaneously. Their main result for the transversities can be summarized as follows. The transversity distribution is positive for the u -quark and negative for the d -quark, the magnitude of Δ_{Tu} is larger than that of Δ_{Td} , while they are both significantly smaller than the corresponding Soffer bounds [13]. From the theoretical viewpoint, the last observation, i.e. the fact that the transversities are significantly smaller than the corresponding Soffer bound seems only natural. It is because the magnitude of the unpolarized distributions are generally expected to be much larger than the polarized distributions. In our opinion, what is more interesting from the physical viewpoint is the comparison of the transversities with the longitudinally polarized distributions.

A main purpose of the present study is to perform a comparative analysis of the transversities and the longitudinally polarized distribution functions in light of the new empirical information on the transversities obtained by Anselmino *et al.* [10]. We shall show that their results already indicate a remarkable qualitative difference between these twist-2 spin-dependent distribution functions, which in turn contains valuable information for clarifying internal spin structure of the nucleon.

As is widely known, the most important quantities that characterize the transversities are their 1st moments called the tensor charges. They are to be compared with the axial charges defined as the 1st moments of the longitudinally polarized distributions. Because of their fundamental importance, they were already investigated in various theoretical models [14] -[24] as well as in the lattice QCD simulations [25],[26]. Within the simplest model of baryons, i.e. the nonrelativistic quark model, no difference appears between the axial and tensor charges. This means that the difference between the axial and tensor charges is purely relativistic effects. As emphasized in [20], however, one must clearly distinguish two types of relativistic effects. The one is dynamical effects, which generates sea-quark polarization. The other is kinematical effects, which make a difference between the axial and tensor charges even though the sea quark degrees of freedom are totally neglected. The existence of the latter effect can most easily be seen by remembering the predictions of the MIT bag model [1],[15], i.e. a relativistic “valence quark model” for the isoscalar and isovector axial and tensor charges :

$$g_A^{(I=0)} = 1 \cdot \int \left(f^2 - \frac{1}{3} g^2 \right) r^2 dr, \quad g_A^{(I=1)} = \frac{5}{3} \cdot \int \left(f^2 - \frac{1}{3} g^2 \right) r^2 dr, \quad (1)$$

$$g_T^{(I=0)} = 1 \cdot \int \left(f^2 + \frac{1}{3} g^2 \right) r^2 dr, \quad g_T^{(I=1)} = \frac{5}{3} \cdot \int \left(f^2 + \frac{1}{3} g^2 \right) r^2 dr, \quad (2)$$

where $f(r)$ and $g(r)$ are upper and lower components of the lowest energy quark wave functions. For a typical bag radius $R \simeq 4.0 \omega_1/M_N$ used in [1], this gives

$$g_A^{(I=0)} \simeq 0.64, \quad g_A^{(I=1)} \simeq 1.07, \quad (3)$$

$$g_T^{(I=0)} \simeq 0.80, \quad g_T^{(I=1)} \simeq 1.34, \quad (4)$$

or equivalently

$$\Delta u \equiv g_A^u \simeq 0.86, \quad \Delta d \equiv g_A^d \simeq -0.21, \quad (5)$$

$$\delta u \equiv g_T^u \simeq 1.07, \quad \delta d \equiv g_T^u \simeq -0.27. \quad (6)$$

This should be compared with the predictions of the CQSM at the model energy scale around $Q^2 \simeq (600 \text{ MeV})^2$, which includes not only the kinematical relativistic effects but also the dynamical effects of nonperturbative vacuum polarization :

$$g_A^{(I=0)} \simeq 0.35, \quad g_A^{(I=1)} \simeq 1.31, \quad (7)$$

$$g_T^{(I=0)} \simeq 0.68, \quad g_T^{(I=1)} \simeq 1.21, \quad (8)$$

or equivalently

$$\Delta u \equiv g_A^u \simeq 0.83, \quad \Delta d \equiv g_A^d \simeq -0.48, \quad (9)$$

$$\delta u \equiv g_T^u \simeq 0.95 \quad \delta d \equiv g_T^u \simeq -0.27. \quad (10)$$

One observes that the biggest difference between the predictions of the CQSM and the MIT bag model appears in the isosinglet axial charge. Note that only the prediction of the former model is consistent with the famous EMC observation, while the latter is not. In fact, any other effective models of baryons than the CQSM fail to reproduce such a small value of $g_A^{(I=0)}$ around $0.3 \sim 0.4$ [27],[28]. (Here, it is assumed to work in the standard $\overline{\text{MS}}$ regularization scheme, in which the net longitudinal quark polarization $\Delta\Sigma$ can be identified with the isosinglet axial charge $g_A^{(I=0)}$.) The isoscalar axial charge is an exception, however. The other observables are less sensitive to the differences of the models. For instance, the isoscalar tensor charges predicted by the above two models are not extremely different as compared with the case of axial charges.

What characteristic features do we expect for the transversities and the longitudinally polarized distributions from the above consideration of the axial and tensor charges ? Broadly speaking, we expect that

$$\Delta q^{(I=0)}(x) \ll \Delta_T q^{(I=0)}(x), \quad (11)$$

$$\Delta q^{(I=1)}(x) \simeq \Delta_T q^{(I=1)}(x), \quad (12)$$

which can alternatively be expressed as

$$\Delta u(x) > 0, \quad \delta d(x) < 0, \quad (13)$$

$$\Delta u_T(x) < 0, \quad \Delta_T d(x) < 0, \quad (14)$$

with

$$|\Delta_T d(x)| \ll |\Delta d(x)|. \quad (15)$$

To make the argument more quantitative, we first compare the CQSM predictions for the transversities and the longitudinally polarized distributions for the u - and d -quarks. As for the longitudinally polarized distributions, we basically use the results of [20] and [29], while for the transversities we use the results obtained in [20] and [21], except one minor modification explained below. (We recall that, in these studies, the Pauli-Villars regularization scheme with single-subtraction was used with the dynamical quark mass of $M = 375$ MeV.) That is, within the framework of the CQSM, the isoscalar polarized distributions survive only at the 1st order in Ω , the collective angular velocity of the soliton, which scales as $1/N_c$ [20],[30]-[32]. On the other hand, the isovector polarized distributions generally receive contributions not only from the leading $O(\Omega^0)$ term but also from the subleading $O(\Omega^1)$ term [20],[29]. The latter subleading correction to $\Delta_T q^{(I=1)}(x)$ was omitted in the calculation by the Bochum group within the same model [22]. However, such $1/N_c$ corrections are known to be important for resolving the underestimation problem of the isovector axial charge $g_A^{(I=1)}$ inherent in the hedgehog soliton models [33],[34], so that we included them in [20],[21]. Unfortunately, the the vacuum polarization contributions to $\Delta q^{(I=1)}(x)$ and $\Delta_T q^{(I=1)}$ contained in this $1/N_c$ correction term (although they are numerically very small) turns out to show somewhat peculiar (slowly) oscillating behavior near $x = 0$, which might indicate some conflict with the basic principle of relativistic quantum field theory [30],[31]. In view of this circumstance, we decided here to retain only the contribution of “valence” level in this subleading terms of $\Delta q^{(I=1)}(x)$ and $\Delta_T q^{(I=1)}(x)$, and drop less important Dirac sea contributions in them. (The terminology “valence” here means quarks in the discrete bound state level coming from the positive energy continuum under the influence of the hedgehog mean field, and it should not be confused with the corresponding term in the parton model discussed shortly.) To get some feeling about the size of the omitted term, it may be useful to see its contribution to the isovector tensor charge. The neglected vacuum polarization contribution to $g_T^{(I=1)}(\Omega^1)$ is 0.04, which is much smaller than the corresponding valence quark contribution of 0.36 and the leading $O(\Omega^0)$ contribution of 0.85 to the same quantity.

In view of the fact that the CQSM reproduces the phenomenologically known longitudinally polarized distributions quite well, we think it useful to give its predictions for the transversities in a simple parameterized form for common use. The fitted transversity distributions consist

of the valence quark part (in the sense of parton model) and the sea (or antiquark) part as

$$\Delta_T q(x) = \Delta_T q_{val}(x) + \Delta_T \bar{q}(x). \quad (16)$$

It turns out that the valence quark parts of distributions are well fitted in the form :

$$\Delta_T q_{val}(x) = a \left[1 + b x + (c x^2 + d x^3 + e x^4) e^{-f x} \right] (1 - x)^g, \quad (17)$$

with

$$\begin{aligned} a &= 0.915395, & b &= 2.93304, & c &= 129.508, & d &= -361.82, \\ e &= 271.256, & f &= 0.231887, & g &= 2.65858, \end{aligned} \quad (18)$$

for the u -quark, and with

$$\begin{aligned} a &= -0.857512, & b &= 12.9987, & c &= 32.6664, & d &= -114.033 \\ e &= 115.414, & f &= -5.89189, & g &= 8.75806, \end{aligned} \quad (19)$$

for the d -quark. On the other hand, The sea quark parts are parameterized as

$$\Delta_T \bar{q}(x) = \left[a e^{-b x} + c x^2 e^{-d x^2} + e x^2 + f x^3 \right] (1 - x)^g, \quad (20)$$

with

$$\begin{aligned} a &= -0.448777, & b &= 0.515693, & c &= -16.9274, & d &= 56.3917, \\ e &= -14.5186, & f &= -5.25201, & g &= 12.2604, \end{aligned} \quad (21)$$

for the u -quark, and with

$$\begin{aligned} a &= 0.439772, & b &= 3.0125, & c &= 1.28447, & d &= 99.8028, \\ e &= -0.437519, & f &= 0.552762, & g &= 2.01257. \end{aligned} \quad (22)$$

for the d -quark. The 1st moments of these distributions gives the above-mentioned tensor charges, i.e. $\delta u = 0.95 (-0.05)$, $\delta d = -0.27 (0.08)$, or $g_T^{(I=0)} = 0.68 (0.03)$, $g_T^{(I=1)} = 1.21 (-0.12)$, where the numbers in the parentheses are antiquark contributions. All these distributions should be regarded as initial distributions given at the low energy scale around 600 MeV. For obtaining the corresponding transversity distributions at the higher energy scale, we recommend to use the evolution program at NLO provided in [35],[36] with the starting energy around $Q_{ini}^2 \simeq 0.30 \text{ GeV}^2$.

Now, we show in Fig.1 the CQSM predictions for the transversities and the longitudinally polarized distributions for the u - and d -quarks evolved to the scale $Q^2 \simeq 2.4 \text{ GeV}^2$, which corresponds to the average energy scale of the global analysis [10]. From this figure, one can

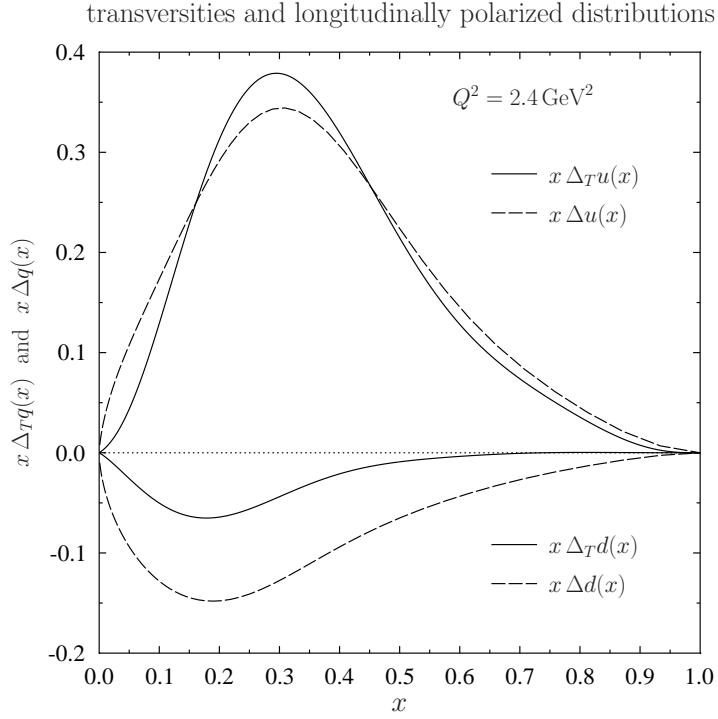


Figure 1: The predictions of the flavor $SU(2)$ CQSM for the transversities (solid curves) and the longitudinally polarized distribution functions (dashed curves) for the u - and d -quarks evolved to $Q^2 = 2.4 \text{ GeV}$.

clearly see that the $\Delta_T u(x)$ and $\Delta u(x)$ have nearly the same magnitude, while the magnitude of $\Delta_T d(x)$ is a factor of two smaller than that of $\Delta d(x)$. As already pointed out, this is a reflection of the characteristic feature $\Delta q^{(I=0)}(x) \ll \Delta_T q^{(I=0)}(x)$.

Next, let us compare our theoretical predictions for the transversities with the global fit by Anselmino *et al.* [10]. The two solid curves in Fig.2 stand for the CQSM predictions for the transversity distributions $x\Delta_T u(x)$ and $x\Delta_T d(x)$ evolved to $Q^2 = 2.4 \text{ GeV}^2$, while the shaded areas represent the allowed regions for $x\Delta_T(x)$ and $x\Delta_T d(x)$ in their global fit. First, one observes that the CQSM prediction for $x\Delta_T d(x)$ is just within the allowed range of the global fit, whereas the magnitude of $x\Delta_T u(x)$ slightly exceeds the upper limit of their fit. (We shall come back later to this point.) Next, although the uncertainties of the global fit are still quite large, a remarkable feature of the transversity distributions seems to be already seen.

The observation that the magnitude of $\Delta_T d(x)$ is much smaller than that of $\Delta_T u(x)$ is exactly what the CQSM predicts. As emphasized before, the reason can be traced back to the

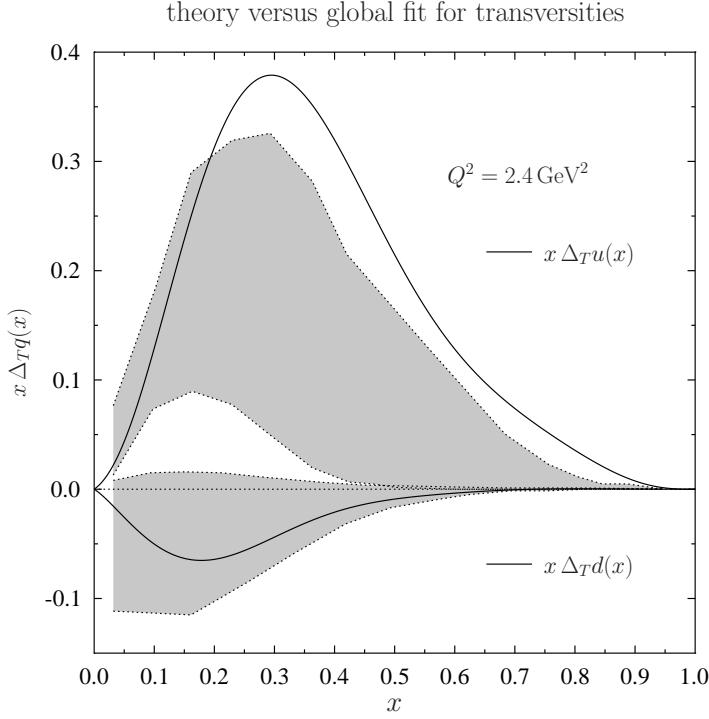


Figure 2: The predictions of the flavor $SU(2)$ CQSM for the transversities (solid curves) in comparison with the global-fit of [10] (shaded areas).

fact that the isoscalar tensor charge is not so small as the isoscalar axial charge. Here, one should clearly recognize the following fact. Although almost all effective models of baryons than the CQSM fail to reproduce very small axial charge of the order of $0.3 \sim 0.35$, the relatively large isoscalar tensor charge is a common prediction of many models including the CQSM. For instance, the MIT bag model (with the constraint to reproduce $g_A^{(I=1)} = 1.257$) predicts $g_T^{(I=0)} \simeq 0.88$ and $g_T^{(I=1)} \simeq 1.46$ [15], which turns out to give remarkably the same numbers as obtained in the relativistic light-cone quark model [18]. The predictions of the hypercentral model given in [24] are also fairly close the the above predictions : $g_T^{(I=0)} \simeq 0.73$, and $g_T^{(I=1)} \simeq 1.21$. Also interesting would be the predictions of the lattice QCD [25],[26], which gives $g_T^{(I=0)} = 0.562 \pm 0.088$ and $g_T^{(I=1)} = 1.07 \pm 0.88$. We recall that for the axial charges the simulation by the same group gives $g_A^{(I=0)} = 0.18 \pm 0.10$ and $g_A^{(I=1)} = 0.985 \pm 0.10$, which denotes that $g_A^{(I=0)} \ll g_T^{(I=0)}$, although the magnitude of $g_A^{(I=1)}$ is obviously underestimated. Somewhat extraordinary are the predictions of the QCD sum rule [17]. It predicts $g_T^{(I=0)} = 1.37 \pm 0.55$ and $g_T^{(I=1)} = 1.29 \pm 0.51$, which dictates that δd is slightly positive. Although this feature

itself is not inconsistent with the result for $\Delta_T d(x)$ obtained in the global fit [10], it would intolerably overestimate the magnitude of $\Delta_T u(x)$. In any case, one can now convince that relatively large isoscalar tensor charge is a common prediction of many effective models. A uniqueness of the CQSM is that it shares this feature with these many models, while it is able to reproduce very small $g_A^{(I=0)}$ or $\Delta\Sigma$.

The reason why the CQSM predicts very small $g_A^{(I=0)}$ or $\Delta\Sigma$ is very simple. Since it is an effective quark model that does not contain the gluonic degrees of freedom explicitly, it satisfies the nucleon spin sum rule in the following simplified form :

$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + L^Q, \quad (23)$$

with L^Q being the net orbital angular momentum carried by the quark fields. On the other hand, according to the physical nucleon picture of the CQSM as a rotating hedgehog justified in the large N_c QCD, it predicts very large L^Q around $2L^Q \simeq 0.65$, which in turn dictates that $\Delta\Sigma$ is small [27]. As a matter of course, in real QCD, the correct nucleon spin sum rule contains the gluon contributions as well :

$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + L^Q + \Delta g + L_g^g. \quad (24)$$

However, the recent COMPASS measurement [37] of the quasi-real photoproduction of high- p_T hadron pairs as well as the other independent measurement by the PHENIX [38] and the STAR collaborations [39],[40], all indicates that Δg is small at least at the low energy scales of nonperturbative QCD. Furthermore, the recent NLO QCD analyses by the COMPASS group as well as the HERMES group with account of the new data on the spin-dependent structure function of the deuteron indicates that [41]-[43]

$$\Delta\Sigma \simeq 0.3 \sim 0.35, \quad (25)$$

which is now surprisingly close to the theoretical prediction of the CQSM, as pointed out in [44]. Combining all the observations above, one therefore concludes that the sum of L_Q and L_g must be fairly large at least in the low energy domain.

Is there any sum rule which gives a similar constraint on the magnitude of the isoscalar tensor charge? The answer is partially yes and partially no. We recall the transverse spin sum rule (BLT sum rule) proposed by Bakker, Leader and Trueman [45], which in fact contains the transversity distributions as

$$\frac{1}{2} = \frac{1}{2} \sum_{a=q,\bar{q}} \int_0^1 \Delta_T q^a(x) + \sum_{a=q,\bar{q},g} \langle L_{s_T} \rangle^a, \quad (26)$$

where L_{s_T} is the component of the orbital angular momentum \mathbf{L} along the transverse spin direction s_T . Unfortunately, this is not such a sum rule, which is obtained as a first moment

of some parton distribution functions. This means that each term of the sum rule does not corresponds to a nucleon matrix element of a local operator. In fact, in the 1st term of the sum rule (26), the quarks and antiquark contributions add, whereas the difference must enter to form the tensor charge $g_T^{(I=0)}$. In spite of this unlucky circumstance, the theoretical analysis based on the CQSM strongly indicates that the transversity distributions for the antiquarks are fairly small, which in turn implies that the 1st term of the sum rule (26) may not be largely different from the isoscalar tensor charge $g_T^{(I=0)}$. Then, if the feature $g_T^{(I=0)} \gg g_A^{(I=0)}$ is in fact confirmed experimentally, it would mean that $L_{s_T}^Q + L_{s_T}^g \ll L^Q + L^g$, i.e, the transverse component of the quark plus gluon orbital angular momentum is sizably smaller than the corresponding longitudinal component. It would certainly provide us with valuable information on the orbital motion of quarks and gluons inside the nucleon.

At this point, we come back to the observation that the global fit for $\Delta_T u(x)$ obtained by Anselmino *et al.* is fairly smaller in magnitude than the corresponding prediction of the CQSM. To get some feeling about the size of the transversities obtained in their fit, one may attempt to estimate the tensor charges from their global fit. Since their fit provides no information on the antiquark distributions, this is of course possible under the assumption that the antiquarks contribute little to the tensor charges. We anticipate that this is not an unreasonable assumption, since the theoretical analyses based on the CQSM indicates that the transversity distributions for the antiquarks are fairly small. Under this assumption, we estimate from the central fit of [10] that

$$\delta u \simeq 0.39, \quad \delta d \simeq -0.16, \quad (27)$$

or equivalently

$$g_T^{(I=0)} \simeq 0.23, \quad g_T^{(I=1)} \simeq 0.55, \quad (28)$$

which is understood to hold at $Q^2 \simeq 2.4 \text{ GeV}^2$. Using the known NLO evolution equation for the first moment of $\Delta_T q(x)$ [46]-[48], we can then estimate the tensor charges at the low energy scale around $Q^2 = 0.30 \text{ GeV}^2 \simeq (600 \text{ MeV})^2$. Here, we use the NLO evolution equation for the 1st moment of $\Delta_T q(x)$ given in [46], which gives

$$\frac{g_T(Q^2)}{g_T(Q_0^1)} = \left(\frac{\alpha(Q^2)}{\alpha(Q_0^2)} \right)^{\frac{\gamma^{(0)}}{2\beta_0}} \left(\frac{\beta_0 + \beta_1 \alpha(Q^2)/4\pi}{\beta_0 + \beta_1 \alpha(Q_0^2)/4\pi} \right)^{\frac{1}{2} \left(\frac{\gamma^{(1)}}{\beta_2} - \frac{\gamma^{(0)}}{\beta_0} \right)}, \quad (29)$$

where $\alpha(Q^2)$ represents the standard QCD running coupling constant at the NLO, while

$$\beta_0 = 11 - \frac{2}{3} N_f, \quad \beta_1 = 102 - \frac{38}{3} N_f, \quad (30)$$

$$\gamma^{(0)} = \frac{8}{3}, \quad \gamma^{(1)} = \frac{724}{9} - \frac{104}{27} N_f, \quad (31)$$

with $N_f = 3$. The result is

$$\delta u \simeq 0.49, \quad \delta d \simeq -0.20, \quad (32)$$

or

$$g_T^{(I=0)} \simeq 0.28, \quad g_T^{(I=1)} \simeq 0.69, \quad (33)$$

at $Q^2 = 0.30 \text{ GeV}^2$. One finds that the magnitudes of $g_T^{(I=0)}$ and $g_T^{(I=1)}$ are both roughly a factor of two smaller than the theoretical predictions of most low energy models as well as those of the lattice QCD. What is meant by this discrepancy is not clear at the moment. Although the global fit carried out in [10] is certainly a giant step toward the experimental extraction of the transversities with minimal theoretical assumptions, one must certainly be cautious about the fact that our understanding of the spin-dependent fragmentation mechanism is still far from complete. Highly desirable here is some independent experimental information on the transversity distributions, for instance, from the Drell-Yan processes [49].

To sum up, we have carried out a comparative analysis of the transversities and the longitudinally polarized distribution functions in light of the new global fit of the transversities and the Collins fragmentation functions carried out by Anselmino *et al.* [10]. We have pointed out that their result, although with large uncertainties, already indicates a remarkable qualitative difference between the transversities and the longitudinally polarized distributions such that $|\Delta_T d(x)/\Delta d(x)| \ll |\Delta d(x)/\Delta u(x)|$, the cause of which can be traced back to the relation between the isoscalar axial and tensor charges, $g_A^{(I=0)} \ll g_T^{(I=0)}$. Combining the standard nucleon spin sum rule and the BLT transverse spin sum rule [45], we can further conjecture that the above relation between the axial and tensor charges would mean $L_{s_T}^Q + L_{s_T}^g \ll L^Q + L^g$, i.e. the transverse component of the quark plus gluon orbital angular momentum would be sizably smaller than the corresponding longitudinal component. We are not sure yet whether this unique observation can be understood as a dynamical effect of Lorentz boost [50]. Finally, for convenience of future analyses of DIS processes depending on the transversity distributions, we gave in the paper the CQSM predictions for the transversities in a simple parameterized form. They can be used as initial distributions given at the low energy model scale around $Q^2 \simeq (600 \text{ MeV})^2$.

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